SUB-CURVILINEAR GULLIES INTERPRETED AS EVIDENCE FOR TRANSIENT WATER FLOW ON VESTA. J. E. C. Scully[1], C. T. Russell[1], A. Yin [1], R. Jaumann[2], E. Carey[3], H. Y. McSween[4], J. Castillo-Rogez[3], C. A. Raymond[3], V. Reddy[5,6], L. Le Corre[5,6], [1]Dept. of Earth and Space Sciences, University of California, Los Angeles, CA, USA (jscully@ucla.edu), [2]DLR, Berlin, Germany, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [4]University of Tennessee, Knoxville, TN, USA, [5]Max Planck Institute, Katlenburg-Lindau, Germany, [6]PSI, Tucson, AZ USA.

Introduction: The view that differentiated solar system bodies that lack or have tenuous atmospheres are completely dry is changing, as exemplified by the discovery of water on the Moon [e.g. 1]. Vesta too has evidence for water: its meteorites contain evidence for aqueous alteration [2,3] and water in primitive melts [4]. Furthermore, Dawn's observations detected a 2.8 µm OH absorption [5] and mineralogically bound OH and/ or H_2O [6]. Also, pitted terrain, interpreted as evidence for degassing of volatile-bearing material, is found in some recent craters [7].

Here we show that sub-curvilinear gullies on Vesta, in the walls of craters containing pitted terrain, are morphological indicators for transient water flow on the surface and also of sub-surface localized water ice, in keeping with meteorite [2,3,4], remote sensing [5,6], modeling [8] and experimental evidence [9].

Flow conditions and morphology: Morphology of terrestrial flow features is commonly used to indicate the flow conditions under which they formed [10]. This approach is adopted by planetary geologists, who use surface morphology, amongst other characteristics, as an indicator of the formational flow conditions of gullies on the Moon and on Mars [11,12,13].

Lunar gullies have simple morphologies: they are straight, parallel to one another and do not intersect to form networks, which is indicative of their formation by dry flow of granular material [11,12]. Martian gullies mostly have a more complex form of a head alcove, sub-curvilinear channels and a depositional apron [13], and many formation mechanisms are proposed for these more complex features [e.g. 14].

Observations: After surveying 170 craters and steep slopes, gullies on Vesta are classified, based on morphology, into two types: linear, identified in 51 locations, most of which are impact craters, and sub-curvilinear and associated features, identified in 10 impact craters.

Linear gullies. Linear gullies are straight, parallel to each other, rarely intersect and have simple network geometries that form parallel networks. They typically originate in alcoves below spurs of more coherent material and are often bounded by levees of talus.

Sub-curvilinear gullies. The type area of sub-curvilinear gullies is found in two craters: Cornelia and Marcia. In these craters the gullies are more sinuous than linear gullies, frequently intersect and have complex network geometries that form sub-dendritic and sub-parallel networks. They typically originate below slumped deposits or in crater walls and commonly end in lobate-shaped deposits. The lobate deposits partially superpose one another and are morphologically similar to terrestrial alluvial fans formed by debris flows.

Pitted terrain: The four craters with pitted terrain on their floors [7] also contain sub-curvilinear gullies in their walls. Sometimes, pitted terrain occurs on the lobate deposits of sub-curvilinear gullies as well as on the rest of the crater floor. Pitted terrain is not observed in craters with only linear gullies. Pitted terrain is morphologically similar to Martian impact-related pitted terrains [15]. Both are interpreted to form by impact-heated degassing of volatile-bearing material [7,15].

Quantified observations: The morphologic dissimilarity between the two gully types can also be quantified: the length to width ratio, junction angles between connecting gullies and number of connections between gullies are all higher for sub-curvilinear gullies.

Interpretations: There are a number of different possible interpretations for the formation mechanism of the vestan gullies, which are discussed below.

Interpretation A: flow of impact melt. Flow of impact melt is considered the least likely formation mechanism for both gully types due to low volumes of impact melt observed and predicted based on calculations [e.g. 16]; the lack of impact melt-like morphologies; and the thermal properties of the gully locations being inconsistent with impact melt [17]. In contrast, the thermal properties of the pitted terrain are consistent with a large impact melt component [17].

Interpretation B: dry flow. The simple morphology of the linear gullies is analogous to lunar gullies and it is likely that they formed by flow of dry granular material. However, since the morphologies of the linear and sub-curvilinear gullies are dissimilar, the principle of morphology indicating flow conditions suggests that some flow condition(s) that formed the linear gullies must be different from the flow condition(s) that formed the sub-curvilinear gullies. In searching for the different flow condition(s), it is found that both types of gullies: i) form on the same ranges of slopes; ii) have similar amounts of material available for flow; and iii) have similar compositions. Also, thermal inertia data [18] indicates that the sub-curvilinear gullies are not formed by flow of relatively finer grained material, which could form more complex morphologies. Thus, no varying flow condition can be found to explain dry granular flow forming the sub-curvilinear gullies as well as the linear gullies.

Interpretation C: transient flow of liquid water.

Since no varying flow condition(s) can be found, it is proposed that the varying flow condition in this case is the flowing material itself. Thus, it is proposed that flow of transient liquid water is involved in the erosion of the sub-curvilinear gullies. Observations that support this proposal are the morphologies of the sub-curvilinear gullies, their formation of complex networks and their association with pitted terrain.

Proposed formation mechanism of sub-curvilinear gullies: Water ice could be trapped and survive for billions of years from depths as shallow as a few meters in Vesta's regolith [8]. Thus, it is proposed that water is sourced in sub-surface ice-bearing deposits that are hundreds of meters deep (Fig. a). Moreover, the clustering of craters with sub-curvilinear gullies may represent this sub-surface ice distribution.

The preferred source of the deposits is reworked syn-accretionary or early depositional ice rather than more recent deposition by ice-rich bodies, because it would be difficult to retain and bury late exogenous ice before it changed phase to a gas. Also, even though volatiles originally present in bodies that differentiated, such as Vesta, are usually assumed to be totally lost [19], quartz veins in a vestan meteorite have been dated to be >4.4 Ga [2], which suggests that at least some water was present early on in Vesta's history.

It is further proposed that sub-surface ice-bearing deposits are tapped by small-medium impacts that increase the temperatures and pressures so that part/ all of the ice melts (Fig. b). Once the water reaches the crater wall it begins to evaporate because water is stable in the gaseous state at vestan surface conditions. However, it is proposed that not all will instantaneously evaporate and that only the top layer will be exposed and evaporating at any one time, hindering the evaporation of lower levels (Fig. c). Thus, water could transiently flow under a temporary protective evaporating barrier before it all evaporates and is lost. Observations support this scenario because no sub-curvilinear gullies are found on escarpments outside of impact craters.

Moreover, preliminary laboratory experiments, focusing on water evaporation vs. time at low pressures (≥2.86 torr), also support this scenario [9]. It is found that 25 ml of water takes ~150 minutes to evaporate at ≥2.86 torr, and that evaporation time doubles with addition of particles (glass beads) [9]. Experiments are initially conducted with ~20°C water, because at low temperatures freezing dominates for the stationary water. In order to investigate evaporation at both low pressures and low temperatures, flowing water will be used to inhibit freezing [9]. These experiments represent the proposed vestan conditions, since water will have entrained particles due to its release from the sub-surface onto a regolith-rich crater wall and water will flow down the wall rather than being stationary.

Finally, after the transient flow, loss, through evaporation, of water that arrives at the crater floors may contribute to pitted terrain formation (Fig. d).

Conclusions: This work indicates that Vesta is more morphologically and compositionally heterogenous and complex than previously thought, and contributes to the newly expanded understanding of fluids on differentiated bodies.

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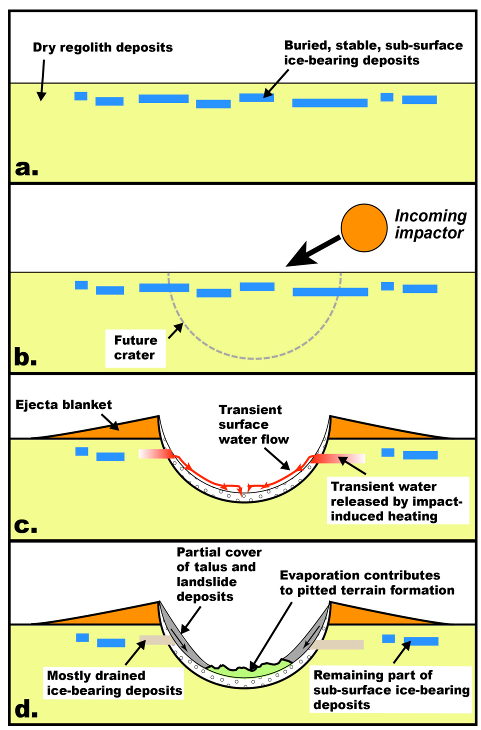

Figures a-d. Schematic illustration of proposed formation mechanism of sub-curvilinear gullies.